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A study of the soil properties important in the application of electro-osmosis

Koonce, Stephen Jack

Rensselaer Polytechnic Institute

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**A STUDY OF THE SOIL PROPERTIES
IMPORTANT IN THE APPLICATION
OF ELECTRO-OSMOSIS**

Stephen J. Koonce

A STUDY OF THE SOIL PROPERTIES
IMPORTANT IN THE APPLICATION

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Stephen J. Linn

A STUDY OF THE SOIL PROPERTIES
IMPORTANT IN THE APPLICATION
OF ELECTRO-OSMOSIS

Stephen J. Koonce
Lieutenant, CEC, USN

Presented as partial fulfillment of the
requirements for the degree of
Master of Civil Engineering
Rensselaer Polytechnic Institute
Troy, New York

June 1954

Thesis

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The author wishes to express his thanks to Professors E.J. Kilcawley and S.V. Best for their help and guidance during the course of this investigation.

LETTER OF TRANSMITTAL

Apt. K.B. #3
Dunn Garden
Troy, New York
May 28, 1954

Faculty
Civil Engineering Department
Rensselaer Polytechnic Institute
Troy, New York

Gentlemen:

I have the honor of presenting this thesis for your approval. It is respectfully submitted as partial fulfillment of the requirements for the Degree of Master of Civil Engineering. It is sincerely hoped that this investigation will assist future investigators and thereby help expand the applicability of this phenomenon for construction problems.

I should like to express my appreciation for the knowledge and guidance that you have bestowed upon me during my stay at Rensselaer.

Sincerely yours,

Stephen J. Koonce
Lieut., CEC, USN

INTRODUCTION

While it is commonly accepted that given enough material and equipment, modern builders can literally put a structure "anywhere", we none the less continue, as have constructors throughout history to seek more efficient methods and materials with which to accomplish our goals.

Oddly enough, soils, one of the most basic of the engineering materials has been one of the last to undergo scientific analysis and investigation yet, paradoxically the behavior of this material during as well as after construction, has a vital bearing on the successful completion and continued utilization of the structure. As a consequence, foundation problems have come to the fore in recent years with the result that tremendous strides have been made toward better understanding of the behavior of soils.

One of the most perplexing and often very costly problems encountered in foundation work, is the unwatering of the construction site in order to permit the construction to proceed in the dry. The very existence of such diverse methods as cofferdams , caissons, sheet pile, bulkheads, the Joosten method, freezing, grouting, and well point and vacuum pumping systems are in themselves mute tribute to the complexity of the problem.

Construction excavations made in fine sands, silts,

loess, and clays which are partially or completely saturated have long been the scourge of builders. So much so, that engineers and builders utilize such sites only with reluctance. However, with our continued national expansion, such sites will of necessity be utilized more frequently in the future.

The most common methods utilized in these areas are the well point and vacuum pumping systems. However, even though these systems are supplementary, their range of applicability is fairly well established and when the pore sizes are below their range limits, these systems are useless.

In view of the limitations of our most modern methods, and the increasing utilization of the less desirable construction sites, it was necessary to seek some new method which would permit construction operations to be carried out in soils whose grain size was too small to permit the stabilization by standard means. For assistance, we have turned to a long known but little understood phenomenon known as electro-osmosis. By this method, fine grained soils can be stabilized through the application of direct current and simultaneously removing the water which collects at the cathodes.

In the last twenty years, electro-osmosis has undergone a considerable amount of laboratory investigation and there

have been some field tests based on various possible applications. Some of these are decreasing the water content as such, increasing the bearing capacity of piles, decreasing the resistance offered by skin friction to the driving of piles, stabilization of slopes and soils through the use of aluminum electrodes, electro-chemical stabilization, and the stabilization of construction excavations.

Some practical applications of this phenomenon have occurred and are described in this paper. However, it is significant to note that the majority of these applications have been under the direction of Dr. Leo Casagrande. He is credited with having done much of the early research in this field and he is quite active in the field at the present time. Yet, he is the foremost of the investigators to indicate that the time has come for a reappraisal of the state of the investigational research in the field with due consideration being given to the lack of basic and fundamental knowledge of the mechanism and contributory factors affecting the applicability of this phenomenon.

It is with the objective of attempting to increase the understanding of the applicability of this phenomenon to the perplexing problems of construction excavation that this paper is undertaken. It is felt that this goal can be attained only through an improved understanding of the basic reactions involved in this process.

The Phenomenon of Electro-Osmosis

As with any scientific process, before any discussions of the practical applications of this phenomenon can be carried on, the basic theory and background of the subject should be reviewed.

In 1807, Reuss discovered that water could be made to flow through a porous diaphragm by the application of an electric potential to the system. Further investigations revealed that there were actually two phenomena associated with the application of electric current to a solid-liquid suspension. If particles of colloidal or near colloidal size were suspended in a liquid and an electric potential applied, the particles will move toward the poles. This movement of solid particles through a liquid is called electrophoresis. Conversely, if the system was predominately solid particles with the interstices filled with liquid, the application of an electric potential causes the liquid to migrate toward one of the poles. This phenomenon is called electro-osmosis.

Quincke, in 1861 formulated the hypothesis that electro-osmosis and electrophoresis could be explained by the consideration that an electrification exists at the contact surface of a solid and a liquid prior to the

Note- Numbers in parentheses refer to the references contained in the bibliography.

application of an electric potential. Then depending on the relative sign, either the solid particles or the liquid will migrate upon the application of an electric potential to the system.

Further consideration of the "Double Layer" hypothesis by Helmholtz, lead in 1879, to his mathematical solution. Although some more recent writers (32, 38) disagree with the Helmholtz "Double Layer" concept, in its revised form, it is currently accepted by the majority of investigators as being the correct approach. In considering a water filled capillary tube, Helmholtz envisioned a film of water being bound to the surface of the capillary by means of the electrostatic forces previously mentioned. His original concept has been modified to say that this boundary film is composed of a fairly thin, fixed or rigid layer and a diffuse or mobile layer which extends a varying distance out into the water of the capillary. A representation of the double layer is shown in fig. 1. In the usual case, the thin rigid layer possesses the negative charges and the thicker diffuse layer is bound to it by virtue of the fact that it contains the predominance of positive charges. The force with which the two parts of the double layer are bound together is called the zeta potential. Fig. 2 is a schematic representation of the zeta potential showing its position with reference to the double layer.

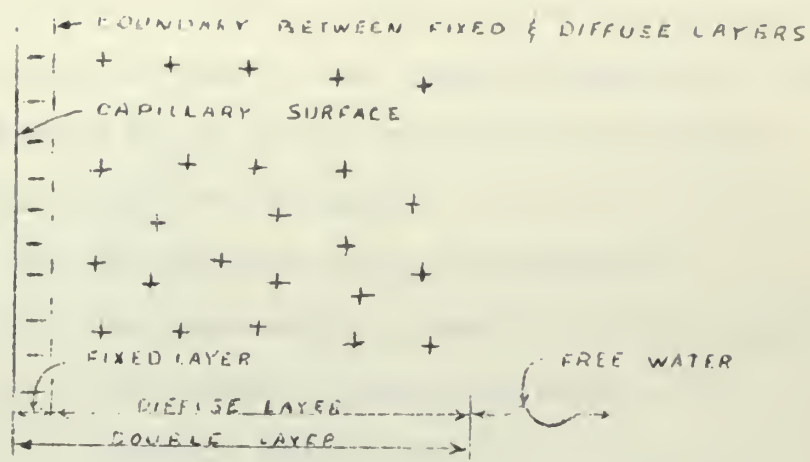


Fig. 1. - Double Layer

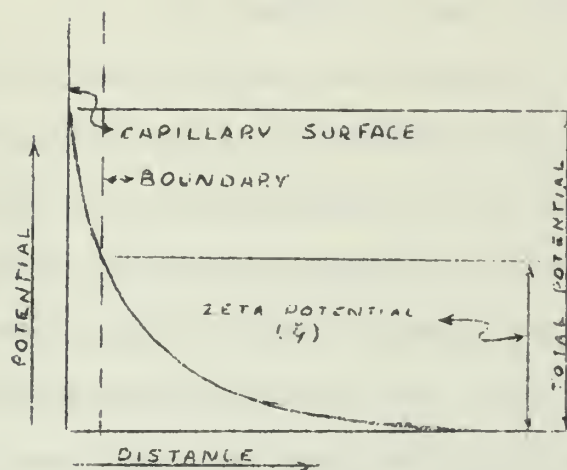


Fig. 2. - Zeta Potential

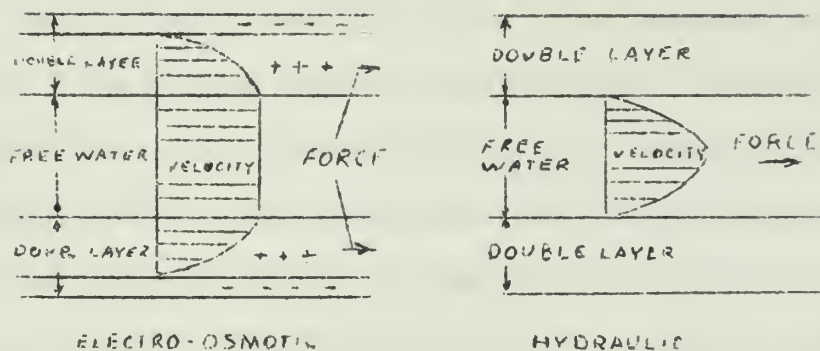


Fig. 3. - Flow Comparison (12)

Helmholtz reasoned that this system was quite similar to a condenser and according to his improved equation, the quantity of liquid which can be moved in a unit time

would be: $q_e = \frac{E D \epsilon^2 r}{4 \eta L}$ in which;

E - the applied electric potential

D - the dielectric constant of the liquid

r - the radius of the capillary

ϵ - the zeta potential

η - the viscosity of the liquid

L - the length of the capillary

If all of the quantities are expressed in grams, centimeters, seconds, and electrostatic units, the quantity of liquid moved will be expressed as cc per sec..

Therefore the water which is actually moved in the electro-osmotic process would come from the diffuse layer and any free water present in the capillary. From fig. 3, it can be seen that the application of an electric potential will cause the water in the diffuse layer (the predominately positive ions) to migrate to the cathode. This moving shell of water will literally drag the cylinder of free water with it. A schematic comparison of electro-osmotic and hydraulic flow with their respective velocities is also shown in fig. 3 from which it can be readily seen that the thickness of the diffuse layer will materially influence the quantity of water moved, provided

of course, the capillary is not too large.

It has been shown that the concentration of the electrolyte directly influences the thickness of the double layer. Gouy reported that the thickness of the double layer varies between 0.96 and 1000 uu for 0.1N sodium chloride and distilled water solutions. Similarly, various investigators established the thickness of the water films adhering to quartz and other silicates at from 40 to 100 uu.

Since the majority of the pores in clay or colloidal materials are of the order of 100 uu, it is immediately obvious that the double layer forms a significant part of the water present in clay and fine grained soils, hence the application of an electric potential will produce significant changes in the properties of these soils.

In view of the fact that the clay fraction is the active soil fraction, it might be well to consider the physiochemical nature of the clay minerals, in order to better understand its contribution to the electro-osmotic process in soils.

Although there are many types and amorphous varieties of clay minerals, only kaolinite and montmorillonite will be discussed since they are considered to represent the extremes of the clay mineral activity range.

The Kaolinite crystal structure, fig. 4 is a 1:1

lattice in which one silica sheet and one alumina sheet combine to form a fixed crystal lattice. This structure is characterized by tight bonding both within the lattice and between adjacent lattices by virtue of the fact that one basal plane has hydroxal ions and the other has oxygen and the secondary forces between the oxygen and hydroxal ions are strong. The charges on this lattice are balanced and therefore it cannot attract external cations or water dipoles except at the unsatisfied negative oxygen bonds at the lattice edges. It's lattice structure does not expand with increasing water content, hence it will adsorb relatively little water and will not exhibit an appreciable amount of swelling. Similarly, it's base exchange capacity is low, between 3 and 15 me. per 100 grams, and it increases with decreasing particle size.

The montmorillonite crystal structure, fig. 5 is a 2:1 lattice in which 2 silica sheets and 1 alumina sheet combine to form a loose crystal lattice. The unit itself is electrically neutral, but it has oxygen ions in both basal planes and therefore it has weak bonding both within the lattice and between adjacent lattices. This weak bonding permits easy ingress of both water dipoles and other cations. In the former instance, the entrance of water between the planes causes extreme swelling to take place with subsequent expansion of the lattice; in the latter

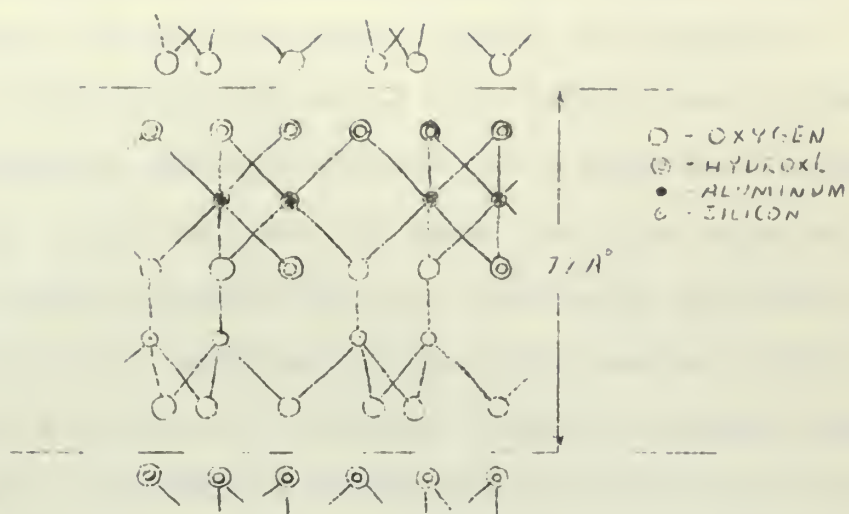


Fig. 4 - Kaolinite

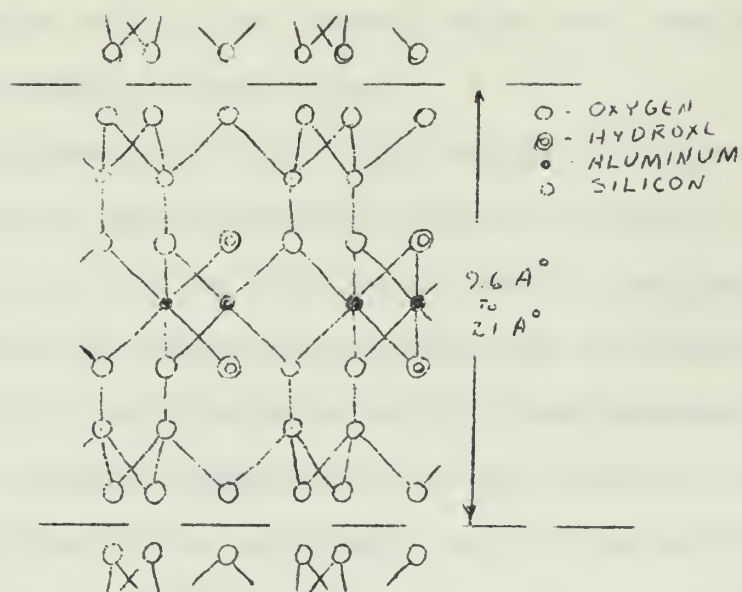


Fig. 5 - Montmorillonite

instance, isomorphisim takes place fairly readily with iron and magnesium ions and frequently those of potassium replacing either the aluminum or the silicon ions in the lattice structure. Montmorillonite has a high base exchange capacity, 60 to 100 me. per 100 grams and this capacity does not increase appreciably with decreasing particle size.

From the brief sketches given of the nature of the clay mineral structure, it becomes readily apparent that the clay-water interfacial relationship lends itself to explanation by a theory similar at least to the Helmholtz Double Layer Concept. This statement quite naturally precludes any considerations such as isomorphic changes within the crystal structure and the distribution and orientation of the force fields within the crystal which are considered to be beyond the scope of this paper.

Further consideration of the applicability of the Helmholtz Concept to the clay-water system as found in soils led Casagrande (9-13) to the conclusion that a similarity must exist between the commonly accepted laws of laminar hydraulic flow, and the flow produced by electro-osmosis. He introduced a potential gradient λ_e , then using a , the cross sectional area of the capillary, and a constant, C , he transformed the Helmholtz equation into a form such that

$$\eta_e = C \lambda_e a, \quad \text{which is quite similar to}$$

$$\text{Poisenelle's Law, } \eta = C \lambda a^2.$$

In considering the total quantity of flow from a system of capillaries, he arrived at the equation $Q = k_e \Delta \phi A$ in which A is the total cross sectional area, $\Delta \phi$ is the potential gradient, and k_e is a pseudo constant which is independent of the size of the capillaries. This form is quite similar to the well known Darcy equation, $Q = k_h \Delta p A$. However, one very significant difference exists between k_e , the electro-osmotic coefficient of permeability and k_h , the commonly recognized hydraulic coefficient of permeability and that is that k_h is dependent upon the area of the capillary and has the dimensions cm/sec whereas k_e is independent of the pore size and has the dimensions cm²/sec volt, which can be reduced to cm/sec for a potential gradient of one volt per cm. This reasoning leads to the conclusion that since k_e is independent of pore size, its value should be the same for such diverse materials as sand, silt, and clay, assuming of course that such variables as the zeta potential and the characteristics of the pore fluid are essentially the same for the various systems. In his discussion of (13), Preece protests very strongly that the concept of an electro-osmotic coefficient of permeability embodying the dielectric constant and the coefficient of viscosity of the pore fluid and the zeta potential is an oversimplification. He says, "Incorporated in these variables are all the unsolved problems of both the electro-

kinetic phenomena and the physiochemistry of the silicate minerals as well." However, notwithstanding the fact that this concept does represent a simplification of an otherwise extremely difficult problem, it has a place in the practical applicability of this phenomenon, as will be discussed later.

Thus it can be seen that the theoretical concepts which are the basis for the explanation of this phenomenon are by no means agreed upon. Yet it is believed that this presentation is a faithful portrayal of the theories most commonly accepted by the majority of the investigators in this field.

Practical Applications

Although it is readily admitted that much has yet to be learned of the actual mechanics of the phenomenon of electro-osmosis, the fact that it does stabilize fine grained soils has been utilized in several instances. Some of the most notable construction projects whose successful completion was due in large measure to this process, will be discussed.

The first full scale application of electro-osmosis was made at Saltzitter, Germany in 1939. In this project, a 20 foot railroad cut was being made through material which consisted of 4 feet of sandy soil overlaying a very soft clayey silt. The excavation had been carried down for a depth of 6 feet when flow slides and the soft flowing condition of the bottom halted further progress. A well point test pit showed that the material was too fine to be stabilized by well points. An electro-osmotic test section 300 feet long consisting of 2 rows of cathodes, 4 inch slotted iron pipes, 30 feet apart and spaced on 30 feet centers, and one line of anodes, 1 inch iron pipe, centered between the cathodes, were placed on each side of the cut. The cathodes and the anodes were driven to a depth of 22.5 feet. A 10 inch sand drain was provided for the cathodes. A potential of 180 volts, later reduced to 90 volts, produced a stabilization such that within a few hours, the

work was resumed and after two days, power excavating equipment was able to operate on the floor of the cut. The water content of the soil prior to treatment was 20 to 24 per cent and the flow to the cathode well points was approximately 100 gallons in 24 hours. Whereas during treatment, the water content was reduced to 14 to 17 per cent and the flow to the cathode well points had increased to nearly 1600 in 24 hours. This reduction of water content so stabilized the soil that power equipment was used to excavate a 1:1 slope which stood throughout the duration of the treatment, notwithstanding the fact that some bad weather was encountered. The entire cut, 5550 feet long, was made using the same type of installations in 300 feet increments. The power consumption for the project reduced from approximately 1.7 kw to 1.2 kw per cathode and in total it amounted to approximately 1 kwh per cu.yd. of material excavated. A sand blanket and drains were installed to maintain the side slopes after the current was stopped.

So successful was the first application of this process, that the contractor decided to use it for some bridge foundations as part of the same project. By applying 90 volts for approximately one week before excavation was started, sufficient stability was produced in this heretofore oozy material to permit an excavation 20 feet

deep and 50 feet wide to be made using vertical side walls and no sheet piles. The power used was 1.4 kw per cathode well and the total power consumption amounted to 2 kwh per cubic yard of material excavated.

The next large scale application of electro-osmosis was made at Trondhjen, Norway. In this project, a large excavation was being made for the construction of some U-Boat Pens. These pens were to be 323 feet by 550 feet and required an excavation 46 feet deep. The soil consisted of a silty clay with sand lenses present throughout.

The contractor's original plan was to use a double row of sheet piling with a berm slope of 2:1 between them. He drove the piling to a depth of 65 feet and proceeded with his excavation. When he got down 23 feet, the piling suffered severe distortion due to a large lateral displacement, at the same time boils began developing and he could no longer keep his excavation equipment on the floor of the excavation lest it become mired.

An electro-osmotic installation was made between the rows of sheet piling. This installation consisted of two rows of slotted 8 inch pipe serving as cathode well points. The rows were 45 feet apart and the cathodes were placed on 30 feet centers. The $1\frac{1}{2}$ inch gas pipe anodes were placed midway between the cathodes and both were driven to a depth of 60 feet. It was originally planned to use a potential

of 90 volts, however, due to the high salt concentration in the soil, this was reduced to 40 volts in order to keep within the amperage capacity of the generating equipment. At that voltage, the current requirement averaged 20 to 30 amps per well.

Prior to the application of the potential, the flow into the wells varied from 0.25 to 11 gallons per hour per well, however, after the current had been flowing for approximately 1 day, this flow rose from 2.5 to 105 gallons per hour per well. The wide range of flow values being attributed to the sand lenses and the variable nature of the soil.

After two days of current flow, the soil was stabilized sufficiently to permit the resumption of the excavation, and it proceeded without mishap down to full depth. In fact, the material stood nearly vertical during the excavation.

It is of interest to note that in spite of the fact that the system removed water in amounts varying between 28,000 and 48,000 gallons per day, the net effect was to lower the water content by approximately 0.5 per cent. Yet, this reduction produced the aforementioned stability. The total energy consumed amounted to 0.4 kwh per cubic yard of material excavated.

After the successful application of electro-osmotic stabilization at the site of the U-Boat Pen project, it was

decided to use it in the construction of a railroad tunnel approach in the Lerkendal Valley near Trondhjen, Norway. The soil was a soft clayey silt and the area was disturbed by old slides. It was determined that an open cut in this material was not a practical approach. Tunneling with a shield was considered to be too expensive and too slow. It was then decided that the area could be stabilized electrically, which would permit an open excavation and construction of the tunnel in the open.

The system consisted of two rows of alternating anodes and cathodes on 30 feet centers and where the excavation exceeded 45 feet, a third row was added. All wells were driven 6 feet deeper than the adjacent excavation.

The potential used was 30 volts and the current averaged 15 amps per well. This potential increased the flow per well from nothing to an average of 25 gallons per day. The water content of the soil was reduced from a value ranging between 25 and 37 per cent to approximately 23 per cent.

The stabilization realized by the application of this system permitted excavations up to 57 feet with side slopes cut on a 1:2 slope.

The application of electro-osmotic stabilization was resorted to in connection with a 50 feet railroad embankment near Ayton, Scotland. A fairly large V-shaped

washout had occurred and it had been hastily replaced with a red marl which was a soft clayey material containing sand, gravel, and boulders as well. It was concluded that a reduction in moisture content would greatly stabilize the fill and since a tunnel for a culvert through the base of the fill was also contemplated, the process of electro-osmosis was counted on to assist in the accomplishment of both goals.

The system consisted of one row of alternating anodes and cathodes on 11 feet centers across the fill along the center line of the tunnel. A potential of 100 volts was applied.

During the 6 month period of operation of this system an estimated 30,000 gallons of water was removed with the result that the water content was reduced approximately 3 per cent and the average strength of the material was increased from 12 psi to 30 psi, an increase of 150 per cent. The power consumption for the period of operation amounted to 61,000 kwh.

An electro-osmotic installation was used to stabilize an excavation for a treatment plant in Bordeaux, France. In this project, an excavation with a diameter of approximately 100 feet was to be carried down 20 feet in a clayey silt. The ground water level was very close to the surface.

After a number of slides developed in the slopes, it

was decided to install an electro-osmotic system. The system consisted of a circumferential row of anodes, 1 in steel bars placed in a 7 inch bore hole filled with coke, on 10 feet centers and 8 feet farther out, a row of 2 inch well point cathodes placed in 7 inch bore holes filled with sand. The electric potential applied varied between 40 and 60 volts, and the total amperage for the system varied between an initial value of 600 amps and a final value of 100 amps after several months of operation.

The amount of water removed by the system decreased from approximately 80 gallons per hour just after the application of the potential, to 8 gallons per hour after three months of operation. This flow resulted in the removal of 635,000 gallons with a total power consumption of 3,700 kwh. It also produced sufficient stabilization to permit the work to be completed without further difficulty, using side slopes as steep as 1:1.

The power consumed amounted to approximately 2.3 kwh per cubic yard of soil treated.

The first successful large scale application of the process in the United States was made in connection with a large excavation for a power plant extension near Bay City, Michigan. This project called for an excavation 31 feet deep over an area approximately 210 feet by 280 feet with intake tunnel excavations to go down another 10.5 feet

within 40 feet of the river.

The soil consisted of 18 feet medium sand underlain by 13 feet of sandy clay, then 19 feet of soft clayey silt, followed by a deep layer of water bearing sand.

The contractor's original construction plan called for steel sheet piling on 2 sides, a double row of sheet piling with earth fill between on the river side, and the fourth side to be left open.

He planned to surround the area with a 2 stage well point system, with provisions for the inner, deeper stage to be used as a vacuum system. With the first stage operating, he had carried his excavation down 21 feet when the sheet piling on one side started moving laterally at the rate of one inch per hour. It was then obvious that the silt could not be handled by ordinary well points or even vacuum pumping. An electrical system consisting of the second stage well points which were on 20 feet centers acting as cathodes and anodes spaced between them was installed. Additional electrodes on 5 feet centers were installed around the intake duct and screen house in the event they might be needed. A potential of 80 volts, later reduced to 60 volts, was applied to the system. Within a few days, excavation was resumed and it was completed without further mishap. In fact, so complete was the stabilization of the entire excavation area that

the excavations for the intake tunnel and screen house were without the use of the additional electrodes and of course without the use of any sheeting.

It was concluded that the cost of the electro-osmotic installation compared with conventional well point dewatering systems.

It is understood that large scale installations of electro-osmosis were made at Joppa, Illinois and Savannah, Georgia but details of these projects are not currently available.

In the vast majority of the cases cited, the process of electro-osmotic stabilization was employed only after the respective contractors had exhausted all possible "Conventional" means of dewatering and slope stabilization and they had failed. It would appear, therefore, that the process of electro-osmotic stabilization of fine grained soils could become a tremendous boon to the construction industry.

Discussion of Important Properties and Applicable Factors

After having reviewed a goodly number of practical applications of this phenomenon, it might be easy to question the need for further investigation. Yet, significantly, the relatively few number of applications in itself raises the question as to why a process which has had such phenomenal success should have been applied so sparingly.

The necessity is clearly demonstrated by two examples. The first is illustrated in a recent letter by a man who was prominent in the construction industry in which he referred to the fact that a contractor in Panama was in process of attempting to set up an electro-osmotic system to stabilize some trenches for a sewer installation, he concluded his reference with the remark "Hope it works!". The second is typified by the following statement of Dr. L. Casagrande (12), "While the tunnel work was in progress I inspected the site, and I had to agree with the tunnel foreman that the soil in the tunnel was much harder than would have been necessary to insure safety of construction".

It is considered therefore, that a discussion of the soil properties and associated factors which constitute the character of the very complex soil-water system, and which contribute to the phenomenon of electro-osmosis is both timely and appropriate.

Grain Size Distribution

Since it has been said that electro-osmosis takes up where well points and vacuum pumping leave off, a discussion of the range and influence of grain size would appear to be a logical starting point.

Based on the hypothesis of the moving cylinder of water dragging a cylinder of free water toward the cathode, it is obvious that a condition will be reached where the ratio of the volume of the moving cylinder to the dragged cylinder will be an optimum. Neglecting the other contributory factors for the moment, this ratio of volume will be in large measure determined by the grain size. Hence, the process of electro-osmosis will be economically applicable between fairly definite grain size limits. Casagrande presented a grain size range within which he considered electrical drainage to be feasible. This range is shown in fig. 6.

Generally speaking, Maclean and Rolfe (35) corroborated the findings of Casagrande, although, they showed that a higher clay content could be present and still have a workable situation. They did this by comparing the quantity of electricity required to remove one gram of water and the clay fraction present in the soil. By clay fraction they meant all particles whose diameter was 0.002 mm and smaller. This comparison is shown in fig. 7.

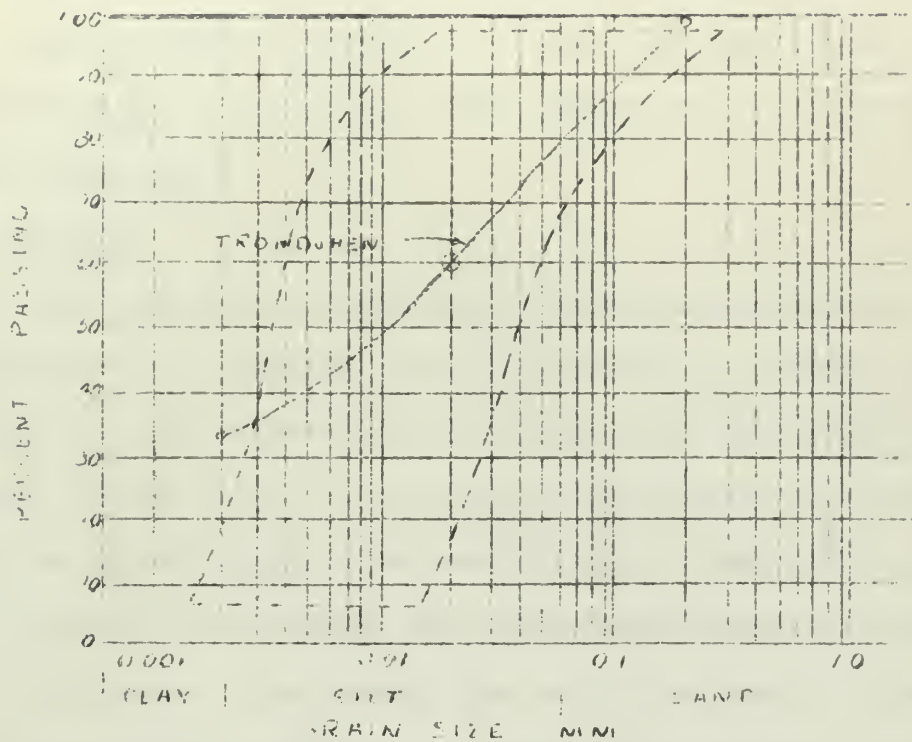


Fig. 6 - Grain Size Range (37)

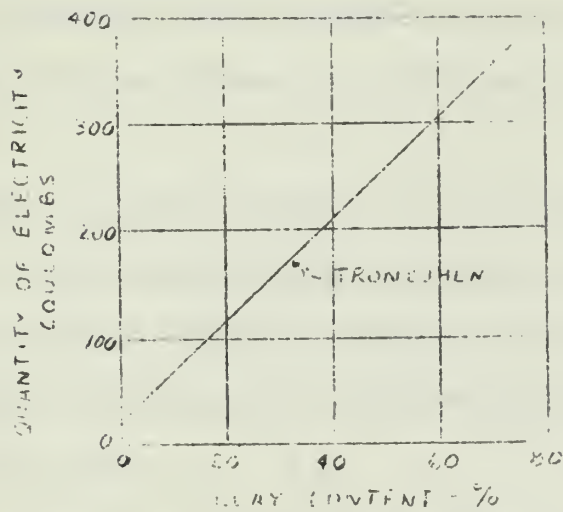


Fig. 7 - Electricity vs. Clay Content (35)

As a matter of interest the position of the material stabilized at Trondhjen, Norway is plotted in both figs.6&7.

From the point of view of practical applicability, the range of grain size distribution appears to be reasonably well established.

Clay Content

Previous investigators have based some of their conclusions on findings using diameters of 0.002 mm and smaller as the criterion for determining the clay fraction present in the soil. It would be incongruous to say that the same percentages of montmorillonite, kaolinite, and rock flour would produce the same physiochemical reactions in a soil mass, even though the particle size of these materials might be identical. The base exchange capacities of kaolinite and montmorillonite themselves would be indicative of the different conditions which prevail at the interface between these clay minerals and the surrounding water.

Therefore, it would seem to be of extreme importance in analyzing the applicability of electro-osmosis to know the relative physicochemical effects of the various materials which comprise the 0.002 mm and smaller fraction of the soil.

Another consideration of importance is the effect of the applied potential on the structure of the clay mineral

itself. Karpoff (29) concluded that potentials of the order of 100 volts or greater decomposed the montmorillonite mineral. The net result of this decomposition is to cause electrophoretic migration of the very small fragments of this montmorillonite mineral to the anode and also a reduction in the base exchange capacity of the treated soil mass. Martin, in his discussion of Karpoff's conclusions, attributed the changes in the soil to reorientation of the montmorillonite particles and decomposition of the micas and feldspars present in the system. Nevertheless, the possibility of decomposition with resultant electrophoretic migration, or the reorientation of clay particles produces similar practical results. The material adjacent to the anode becomes denser with an associated decrease in pore size. The net effect being an increased resistance to current flow, increased thermal consumption of electrical energy, and a general decrease in the efficiency of the system. The drying and cracking of some of the experimental studies namely (14) and (51) might very well be attributed in part at least, to this reason.

It seems imperative, therefore, that more information on the destructive effect of higher potentials on the clay mineral structure be obtained.

Adsorbed Ions

It has been proven that the type and amount of adsorbed

ion vitally affects the physicochemical characteristics of clay minerals. Similarly it would appear that the type and amount of adsorbed ion would play a significant role in the mechanics of the electro-osmotic process.

The force of attraction between ions and the clay particle, as illustrated by Eaver (2), can be calculated using Coulomb's Law, $F = k \frac{q_1 q_2}{d^2}$ in which d is taken to be r_a , the radius of the anion plus r_c , the radius of the cation. One very significant modification must be considered however, and that is that the radii of the ion must be taken as the hydrated radii. It is well established that the hydrated radius of ions follows the series $Li > Na > K > Rb > Cs > H$. Consequently, the strength of the adsorptive bond between the particle and the adsorbed hydrated cation will vary in the reverse order of this series. This fact has been proven by the establishment of the Lyotropic Series which may be stated generally as $Li < Na < K < Rb < Cs < H$, with the position of Li changing somewhat depending on the particular system.

Therefore, based on the premise that at least part of the water which is set in motion in the double layer is water of hydration, the amount and type of adsorbed ion would be extremely important factor in any consideration of the applicability of electro-osmosis. The significance of this fact could be divided into two considerations,

namely, how much electrical energy will it take to displace or replace the adsorbed ion and how much of the water present in the system is represented by the water of hydration of the cations, which can be expected to be removed by the cation migration.

According to Casagrande, (7), one of the significant conclusions arrived at by Macey (34) was the fact that the effect of diverse cations on the shear strength of clays has been found to be small, especially at higher moisture contents. Yet, Poisson (43) found that a sodium saturated clay was turned into a more compressible clay which shows a marked increase in tendency to swell. Similarly, Murayama (40) found that the untreated Yoshidayama clay (pH 6.20) could not be stabilized using aluminum electrodes. It would appear therefore, that the true effect of the adsorbed ions on the shear strength is not fully understood. There is contemporary research in progress investigating the effects of adsorbed ions on the engineering properties of soils, however, it is considered necessary that more basic experimental research be undertaken to determine the participation of adsorbed ions in the stabilization produced by electrical means.

Ground Water Conditions

In fine granular soils, the existence of a hydraulic head can easily produce a quick condition which can be

ruinous for construction excavations. When these materials are too fine to permit conventional pumping, electro-osmosis can be used in a purely hydraulic sense to accomplish the required temporary stabilization. As previously shown, the amount of electrical energy required to expel one gram of water decreases in direct proportion to the decrease in per centage of the clay fraction present. Therefore, it is entirely possible that a reversal of flow such as that shown in fig. 8 could very well produce the required stabilization. It is felt that no further description of this type of stabilization is necessary since it actually would be a true supplement to vacuum pumping. Yet, it is felt that a consideration of the soil itself, the determination of the amount and type of clay mineral present, and an analysis of the sub-surface water conditions could very well lead to soil stabilization produced not by electrochemical means, but by the consolidating effect resulting from seepage forces produced by the electrically induced flow.

It seems appropriate at this point to deviate slightly in order to discuss electro-osmotic consolidation and induced pore water tension, since these products of the process are vitally affected by the presence or absence of a continuous source of water entering the system.

Immediately upon the application of an electric potential, the pore water begins to flow, generally toward

the cathode. This movement of water produces some significant effects on the soil structure. In a system where there is no free water access to the anode the water content decreases and the soil begins to consolidate around the cathode with resultant formation of shrinkage cracks. In fact, in the case of clay, a laminated structure is developed near the cathode when high potentials are used. Pore water tension develops throughout the soil roughly following the decrease in water content. These tensions are usually sufficient to produce cracks in the material adjacent to the anode. Wang (57) measured the pore water tension at a value of 350 cm. which represents a considerable stress on the compressible structure of a soil mass. Similarly the consolidating effect of electro-osmosis was shown by (18) to be as much as that produced by a static loading of 1 ton/sq.ft., although using lower potential gradients, it is usually equivalent to a loading of 0.1 to 0.4 tons/sq.ft..

It would seem therefore, that much of the practical success of electro-osmotic stabilization is due to the combined effects of the weight of the overburden and the induced consolidation.

Another interesting consideration relative to ground water conditions, was demonstrated by Karpoff (29). He showed that whereas the lowering of the water surface in

his experimental model by electrical means required 20 minutes, its recovery against a 7 inch hydraulic head required 178 hours. This observation could lead to economies which might be realized through intermittent pump operations. However, this possibly would always be a function of the ground water flow condition for each particular site.

Chemical Composition of Ground Water

The chemical composition of the ground water plays a very significant role in the applicability of electro-osmosis. The first consideration is the fact that the type of adsorbed ions and possibly the isomorphic exchanges, are largely dependent on the ground water for their source. Therefore, lacking better means of identification, the composition of the ground water could provide a basis for estimating the type of ions adsorbed by the particles.

The dielectric constant of the ground water determines to a large extent the portion of the current which will flow through the free water phase of our idealized soil capillary, and which portion will flow through the diffuse part of the double layer, thus producing the electro-osmotic effects previously mentioned.

Intimately associated with the consideration of the dielectric constant of the pore water is the zeta potential. For high electrolytic concentration, the zeta potential can be reduced to zero or it is possible to reverse the

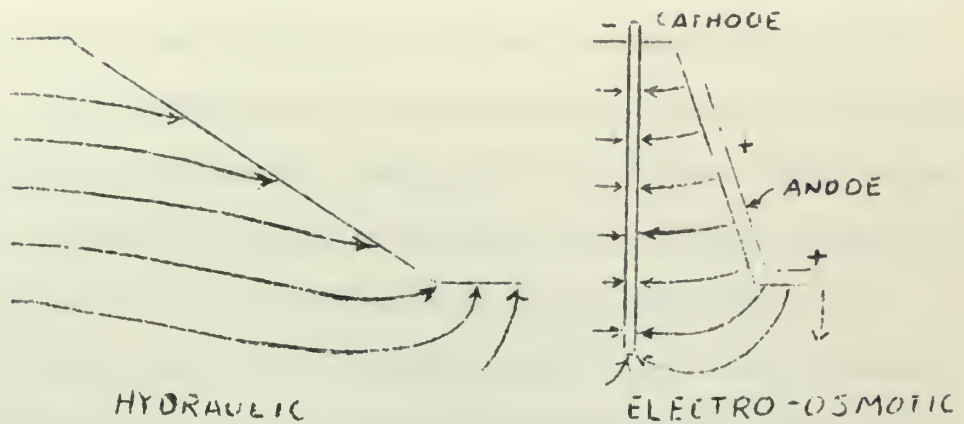


Fig. 3 - Slope stabilization by reversal of Flow (12)

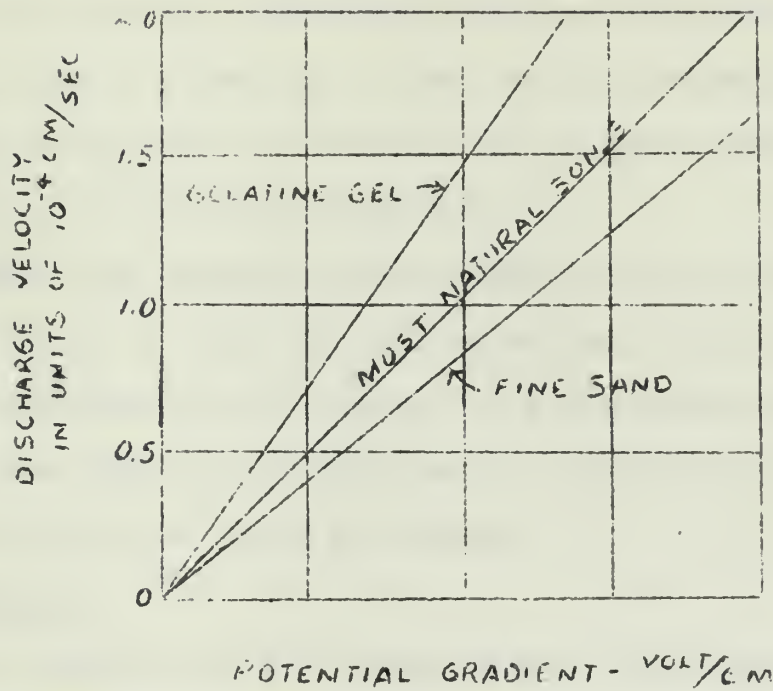


Fig. 9 - Electro-Osmotic Flow vs. Potential Gradient (12)

charges in the double layer. The net effect of these possibilities is to stop the electro-osmotic flow entirely and to reverse the direction of flow respectively. Either of which could eliminate the possible applicability of the electro-osmotic process. Casagrande (12) states that zeta potential does not vary much within the ordinary range of concentration of electrolytes found in soils. Yet, in several of the practical applications cited, the determination of the voltage to be applied was based on the limitation of the current generating capacity of the equipment. The current requirement in turn was a function of the concentration of the electrolytes in the pore fluid. It is felt that the future applications of electro-osmosis will be largely in marine or near marine building sites and the electrolytic concentrations in these areas are certainly of significant magnitude.

Before the complete understanding of the contribution of this factor to the over all mechanism of the electro-osmotic phenomenon is attained, it would appear that more data on the effect of variations in electrolytic concentration of the pore water is needed.

Permeability

The consideration of permeability, both hydraulic and electro-osmotic, has been delayed until last because this soil property embodies the crux of the complex

problems which beset the applicability of electro-osmosis for purposes of soil stabilization. According to Taylor (52), the well known hydraulic coefficient of permeability is dependent on the second power of a dimension representative of the average grain size, the properties of the pore fluid, the void ratio, the shapes and arrangements of pores on the soil structure, and the amount of dissolved gases within the pore fluid. To this statement should be added, the effect of adsorbed ions on the pore space available for flow, as shown in fig. 3. As previously mentioned, the electro-osmotic coefficient of permeability is dependent on essentially the same factors with the exception of the area of the capillary as denoted by the average grain size factor in the hydraulic coefficient of permeability. For the grain size range with which we are concerned, the hydraulic coefficient of permeability has been found to vary from values of the order of 10^{-2} cm/sec to 10^{-4} cm/sec. This represents a tremendous range of materials which would tax the ingenuity of any construction man faced with them as building materials. Yet, according to Casagrande (13), the electro-osmotic permeability ranges between 0.2×10^{-4} and 0.7×10^{-4} cm/sec for a potential gradient of 1 volt/cm. Fig 9 shows this range. From his numerous experiments and practical applications, Casagrande has

concluded that a value of 0.5×10^{-4} cm/sec for 1 volt/cm is the average value for the great majority of soils in their natural state, when saturated.

While it is readily admitted that the concept of an electro-osmotic coefficient of permeability attempts to place an empirical value on a grouping of the most complex variables in the entire field of Soil Mechanics, it is still felt that such a concept has a definite place in the field. From a practical standpoint, a comparison of the order of magnitudes of the hydraulic coefficient of permeability and the electro-osmotic coefficient of permeability will assist the engineer in deciding whether or not future investigations of the possible applicability of electro-osmosis are indicated.

The foregoing discussion of pertinent soil properties and associated factors is not presented as being a complete and comprehensive analysis of all the factors contributory to the successful application of electro-osmosis for temporary soil stabilization. It is presented primarily to illustrate the lack of basic and fundamental knowledge of the actual mechanism of this phenomenon.

Recommendations

Since 1935 a great deal of laboratory effort has been consumed in first verifying the possibility that electro-osmosis can stabilize soils, and secondly in an attempt to define the phenomenon and to determine the mechanism by which the stabilization is actually effected. In the first instance, the number of experiments, coupled with the accounts of the practical applications clearly substantiates the premise that increased stability can be produced in soils by electrical means. The second field of endeavor has proven to be the more difficult by far. Numerous investigators have approached the problem by conducting extensive and comprehensive experimentation using naturally occurring soils. These data contribute a considerable amount to the general fund of scientific knowledge, but their interpretation and significantly, their application to soils other than the test material has so far been exceedingly difficult, if not, generally speaking, impossible. It is with the second field of investigation that this work is primarily concerned.

It is considered that the clay fraction, the active fraction, is by far the most important single factor in any consideration of the applicability of this process.

This should by no means be construed to imply that there are no other significant factors to be considered,

but merely to state that any line of investigation of the mechanism of this phenomenon must be based first of all on an understanding of the role of the clay fraction in the over-all picture. To the writer's knowledge, only one investigation (7) has been undertaken with this concept as a premise. However, it is the opinion of the writer that basic research is required to determine the effects of the application of an electric potential on the clay-water-ionic relationships. Further, this research must be undertaken before it will ever be possible to predict the stabilizing effects of the application of electric potentials without the use of large scale field tests and/or detailed model studies.

It is with the foregoing principle in mind that the following lines of investigation are recommended as being essential to the thorough understanding of the mechanism of the electro-osmotic process and its stabilizing effects on soils.

1. Clay Content

The difference in the amount of surface activity in the various clay minerals and its effect on the electro-osmotic process has not been clearly delineated. It is considered that this differential is a significant factor in the application of electro-osmosis.

This factor could be analyzed if various per centages

of standard known samples of Kaolinite, Illite, and Montmorillonite mixed with clear sand whose grain size falls within the range previously given, and the slurried mixture then subjected to an electric potential. The samples should all be saturated with the same ion to eliminate any possible differential due to different ionic adsorption energies. The same type of electrodes and the same liquid, tap or distilled water, should be used for the same reason. These different mixtures of a known clay and inert sand should then be subjected to the same electric potential, any convenient voltage, provided it is well below the controversial 100 volts, and the amount of water expelled in a convenient time measured.

With the data obtained from these experiments, the effect of the different types of clay minerals on the energy required to expel a given amount of water should be clearly defined. This information should supply a clear understanding of the role of the type of the clay mineral present in a soil on the stabilizing effects obtainable by applying an electric potential.

2. Clay Mineral Structure

Of considerable import is the effect of electric potentials on the clay mineral structure itself. Whether this effect takes the form of forced isomorphism or the actual destruction of the crystalline structure itself

remains to be seen.

It is submitted that in order to determine these effects, the experiments must be conducted on standard, known materials. In order to establish the range of effects, these known materials should consist of purified samples of Kaolinite, Illite, and Montmorillonite. These materials could then be subjected to various electrical potentials and the crystalline structure analyzed to detect any changes. More specifically, a small amount could be placed in an appropriate trough or tube and subjected to an electric potential range of 10 to 150 volts. A 10 volt increment should be sufficient. It would be advisable to conduct a separate run for each increment, to eliminate the possibility of the preceeding potential having put a strain or deformation in the crystal and thereby accelerating the effects of the next higher potential increment. Inert electrodes such as platinum or possibly carbon should be used to minimize any possible base exchange or isomorphic effects. Saturating the sample with hydrogen ions prior to its use will also help reduce these effects. In this connection, distilled water should be used to make the slurry. A reservoir of distilled water leading to the anode should be provided to minimize any possible drying out of the material adjacent to the anode and hence coloring the test results with thermal effects on the crystal structure.

In view of the fact that Karpoff (29) found that 100 volts applied for a period of 152 hours produced structural changes in a natural material, it would seem advisable that the proposed tests be run for a period of 200 hours, with suitable intermediate sampling times say 24 hours.

The samples would then be analyzed using either the X-ray defraction method or if it proves to be sufficiently accurate, the Goniometer-Spectrometer. The analyzed samples should be taken from the area adjacent to the anode, the cathode, and possibly one intermediate point in the test specimen.

It is considered that the data obtained from these experiments would clearly define the effect of an electrical potential on the crystalline structure of the clay minerals.

3. Adsorbed Ions

In order to evaluate the effect of various types of adsorbed ions on the applicability of electro-osmosis it will be necessary to resort again to the use of standard known clay minerals, Kaolinite, Illite, and Montmorillonite. The use of inert electrodes and distilled water to minimize and control the type of ion involved in the base exchange process is mandatory. Successive slurries of various ionic saturation can be subjected to a convenient electric potential again keeping well below the controversial 100 volts for a convenient period of time. The amount of water

expelled should be measured. Atterburg Limits should be run periodically during each test run for the material adjacent to the anode, the cathode, and the material midway between the electrodes.

The difference in the amounts of water expelled should be a good measure of the relative amount of the water expelled by the electro-osmotic process which is directly due to the water of hydration of the ions. The Atterburg Limit changes as compared to the electrical energy required to produce them, should be a good measure of the effect the various ions have on the stability producible by electro-osmosis.

4. Chemical Composition of the Pore Water

In order to evaluate the effect of the electrolytic concentration, it is considered that tests using various concentrations of ions in the pore fluid must be run. These tests could be run using any known clay mineral and then saturating it with the same ion whose concentration will be varied in the pore water. Inert electrodes should be used to minimize the base exchange effect. Any convenient voltage, say 60 volts, will suffice. A slurry should then be made using water of a known electrolytic concentration and the sample container should be connected to a reservoir of the same water so that free flow is admitted to the anode face. The electric potential should then be applied for a

reasonable period say 4 hours , and the quantity of water expelled measured. The same procedure should be repeated . with an increased concentration and the quantity of expelled water measured. The comparison of the quantities of water expelled and the electrical energy required to expel them, should provide a conclusive measure of the effect of variations in electrolytic concentration of the pore water on the electro-osmotic process.

These tests should include the electrolytes usually found in ground waters, Ca, Na, Fe, and possibly K.

As a matter of interest, the clay mineral could be saturated with ions other than those of the pore fluid and similar tests made to attempt to evaluate the variations in zeta potential when the fixed layer contains diverse ions.

While it is readily admitted that such investigations as electro-osmotic consolidation and pore water tension studies are very important to the over all knowledge of electro-osmotic effects, it is felt that these "secondary" effects will ultimately be explainable in terms of the basic knowledge now being sought. Therefore, the foregoing lines of investigation are proposed not as representing the only worthwhile investigational topics, but merely in an attempt to outline the minimum requirements of basic and fundamental research so vital to a thorough understanding

of the electro-osmotic phenomenon.

Summary and Conclusions

The evidence obtained thus far from the investigations analyzed in the preparation of this paper indicates that the phenomenon of electro-osmosis, as applied to soils, is primarily one of forced base exchange confined for the most part to the surface of the clay mineral. This confinement to surface activity is dependent on the amount of the applied potential and the composition of the inter-particle liquid with higher potentials probably producing changes in the crystal structure of the clay mineral.

The fact that the application of this phenomenon to soils can be made to produce stabilization sufficient for construction purposes in soils never before capable of being stabilized is known. Yet, the mechanism by which this stabilization is produced and the contribution of the various soil properties and other associated factors are not only not understood, but very little basic research toward that end has been accomplished. It is considered therefore, that the undertaking of basic research is of utmost importance to the complete understanding of this phenomenon.

It is believed and sincerely hoped that the outline of required research presented by this paper will contribute to a better understanding of the basic principles of electro-osmosis.

It is believed that the day is not too far distant, when our understanding of this phenomenon is complete enough that the acquisition of a relatively few significant facts about the soil and site in question will be sufficient to predict the applicability of electro-osmosis to the stabilization of the soil. When that day comes, building locations and designs will be made based on the fact that electro-osmosis can produce a stabilization in fine grained soils and maintain it long enough for construction requirements.

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